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THE PRODUCTION EFFECT ON THE PERFORMANCE OF PANELS CAST WITH SELF-COMPACTING FIBRE REINFORCED CONCRETE

Luca Bartoli (1), Steffen Grünewald (1), Roel Schipper (1), Yuguang Yang (1) and Dick Hordijk (1)

(1) Delft University of Technology, Delft, NL

Abstract

The strain-hardening behaviour of cementitious composites is the result of a synergistic behaviour of the cement matrix and fibres in a cracked cross-section. The distribution and orientation of the fibres are essential in order to obtain such favourable tensile behaviour. Strain-hardening composites can be applied and are especially useful in structures, which are difficult to reinforce effectively with traditionally placed rebars. Examples of such structures are slender and thin elements, like double-curved precast panels, which also do not provide sufficient concrete cover.

An experimental study was executed on the effect of the production method on the performance of panels produced with self-compacting fibre reinforced concrete. Different casting methods were applied such as free flow condition and controlling the flow by guides. Flexural tests were executed that indicate the influence of the casting method. The distribution and orientation of the steel fibres was studied by image analysis on pictures taken from cut cross-sections. This paper discusses results of a study that aimed at utilising the potential and improving the performance of self-compacting fibre reinforced concrete for the case of thin panels.

1. INTRODUCTION

1.1 Self Compacting Fibre Reinforced Concrete

The use of Fibre Reinforced Concrete (FRC) has arisen in the past decades as an alternative to conventional reinforcement in concrete, to compensate its weaknesses, which are a low ductility and relatively low tensile strength, due to the brittle nature of concrete.

The benefits achieved with the fibres are for instance the bridging of cracks, an enhanced ductility and flexural strength but also enhanced fire resistance and shear strength. However, the widespread use of FRC is still limited, mainly due to the lack of generally accepted and reliable design guidelines and the often high scatter of the mechanical responses. This high scatter is partially due to a non-uniform distribution and orientation of fibres in the matrix, which, as a result, leads to a high material safety factor.

The use of Self-Compacting Concrete (SCC) represents a valuable solution to the aforementioned lack of uniformity. In fact, one major advantage provided is that it does not require any external vibration: the fresh state properties of SCC guarantee a more uniform distribution of fibres in the matrix. Reducing, or even annulling, the phenomenon of segregation and the presence of zones with reduced fibre dosage or no fibres, drastically decreases the aforementioned scatter. Moreover, the use of an optimized mixture combined with the flowability of SCC, allows influencing the alignment of fibres through an appropriate design of the entire casting procedure. The fibres' orientation is one of the most influential parameters on the post-cracking behaviour, and thus, being able to tailor the orientation in the direction of the principal tensile stress could lead to superior mechanical and structural performances.

1.2 Flow situations

The flow of a cementitious composite is activated only if a stress higher than a critical value is applied [1]. In an extended study the effect of the flow on the fibre orientation was studied and related to the flexural behaviour of prisms cut from thin panels [2]. The two principal flow types are defined as:

- the flow dominated by shear stresses
- the radial flow.

The difference of drag forces on the fibre-ends exerts a torque on the fibres which affects the alignment of the fibres. The channel flow is an example of the first type. It is characterized by a parabolic profile of flow velocity. This profile forces them to rotate and to align along the direction of the flow. Concerning the radial flow, the wall-effect caused by the sides of the formwork can be neglected because of the distance from the casting point and they do not influence the flow. The velocity profile is formed by concentric iso-velocity circles and the velocity decreases outwards radially from the casting point. For this second flow type the fibres tend to align perpendicularly to the flow. Moreover, the described phenomena are correlated with the yield stress of the material [3]. A material characterized by a low yield stress, like SCC, shows more a pronounced effect on the orientation of the fibres. For this reason, SCFRC is a suitable material to achieve the objective of developing a tailored material.

2. EXPERIMENTAL SET-UP

2.1 The mixture

The mixture used for the experimental study [4] is shown in Table 1. The optimized SCFRC's mixture was developed by Grünewald [5], and was intentionally chosen since many tests already were executed before with this mixture. The slump flow test showed a good flowability of the fresh mixture. The 500 mm diameter (T50) was reached in 2.8 seconds. In the hardened state, the material is characterized by a mean compressive strength (standard deviation 1.32 MPa) of 70.91 MPa and a mean splitting tensile strength (standard deviation 0.55 MPa) of 8.44 MPa at an age of 28 days after casting.

Table 1: SCFRC mixture composition

Component	Mixture [kg/m^3]
Steel fibres (Dramix 80/60 BP)	60
CEM I 52.5 R	269
CEM III 42.5 N	143
Fly ash	173
Superplasticizer (Glenium 51)	3.28
Water	181
Sand (0.125-4 mm)	1032
Coarse aggregate (4-16 mm)	481

2.2 Mould and preparation of specimens

Three panels were produced, modifying the casting process to induce a preferable orientation of the fibres. The dimensions of the mould were 800/500/60 mm (L/W/H). In two of the three panels, rigid plastic guides were inserted in the formwork, in order to simulate a channel flow and take advantage of the wall-effect.

Table 2: Outline of the experimental study

Panel 1	Forced flow: straight guides inside the formwork
Panel 2	Free flow inside the formwork: no guides.
Panel 3	Forced flow: 45° oriented guides inside the formwork

The following pictures (Figures 1-3) illustrate the casting procedure of each panel. Moreover, the drawings show the position of the guides, the preferred orientation of fibres and the position of the extracted specimens.

Panel 1

Using a casting aid the concrete was poured into the four channels with the help of buckets at a flow rate of about 0.3 l/s. The fibres are expected to orient along the walls of the guides.

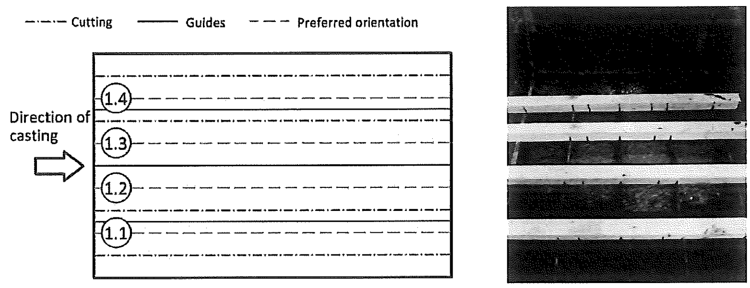

Figure 1: Set-up Panel 1: guides' position; cutting sections; predicted orientation (left). Formwork and casting procedure (right).

Panel 2

The concrete was poured into the formwork from one side, directly from a bucket. As shown in Figure 2, the casting point was in the middle of the longest side of the formwork, the location coincident with the section where the notch was cut afterwards. The flow rate was about 0.5 l/s. The fibres are expected to align perpendicularly to the flow direction.

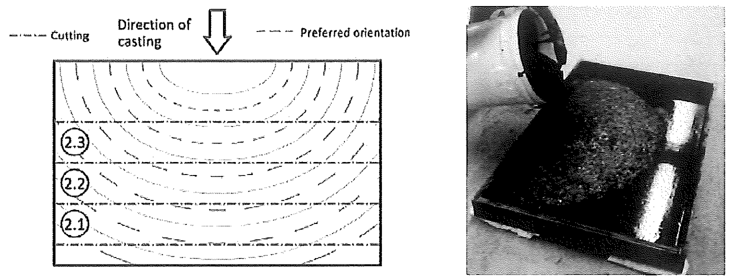

Figure 2: Set-up Panel 2: cutting sections; predicted orientation (left). Formwork and casting procedure (right).

<u>Panel 3</u>

The concrete was poured directly into the channels, without a casting aid with a slope, using contemporary two buckets in order to keep a constant flow rate, which was about half of the rate of Panel 1 (about 0.15 l/s).

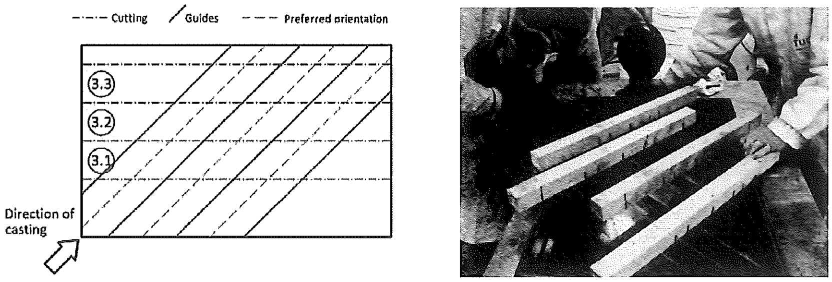

Figure 3: Set-up Panel 3: guides' position; cutting sections; predicted orientation (left). Formwork and casting procedure (right).

Due to the high flowabiliy of the mixture that was used, no vibration or manual compaction was needed for the casting process. Then, for Panels 1 and 3, as soon as the casting was completed, the guides were removed slowly from the mould when the concrete still was flowable, in order to prevent their effect on the distribution of the fibres. The lifting rate of the guides was about 1 cm/s.

2.3 Execution of bending tests

Deformation-controlled three-point bending tests were performed in the Stevin 2 Laboratory at Delft University of Technology. The tests were conducted on notched specimens (L/W/H: 800/100/60 mm; notch depth of 10 mm) with a span of 650 mm. The crack-mouth opening (CMOD) was registered with two linear variable displacement transducers (LVDT). The control signal was the vertical displacement of the machine and the force impressed and crack opening were also recorded. The rate of deformation was the same for all specimens: 0.1 mm/min until a crack opening of 2 mm and 5 mm/min beyond 2 mm.

3. FLEXURAL BEHAVIOUR OF CUT SPECIMENS

3.1 Flexural behaviour

The development of the stress–profile of a SCFRC cross-section can be divided into three main stages. Firstly, the material shows a linear elastic behaviour until the formation of the first crack. Secondly, during the early crack propagation, the concrete is affected by a rapid loss of stiffness and the load-carrying capacity is gradually transferred to the fibres. Eventually, in the tensile zone, the strengthening contribution is provided only by the activated fibres.

3.2 Experimental results

Table 3 show an overview of the three-point bending tests. The post-cracking behaviour of the specimens is illustrated in the three following figures (Figures 4-7), in terms of Load-CMOD relation.

Table 3: Overview of the results

	SP 1.1	SP 1.3	SP 2.1	SP 2.2	SP 2.3	SP 3.1	SP 3.2	SP 3.3
Maximum load [N]	2657.8	2454.9	2708.8	2458.6	2966.8	1389.5	1901.3	1610.7
Crack width [mm]	0.42	0.29	0.82	0.30	0.59	0.04	0.61	0.97

Panel 1 [Straight guides]

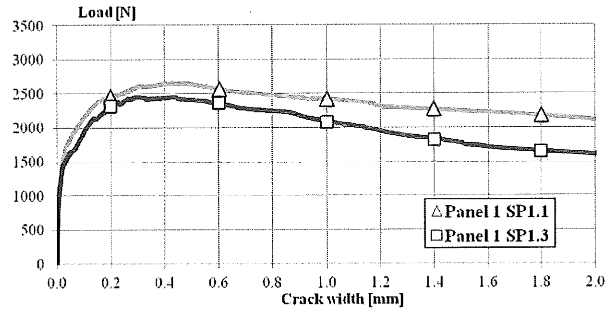

Figure 4: Test results specimens from Panel 1 (up to 2 mm)

Panel 2 [Free flow]

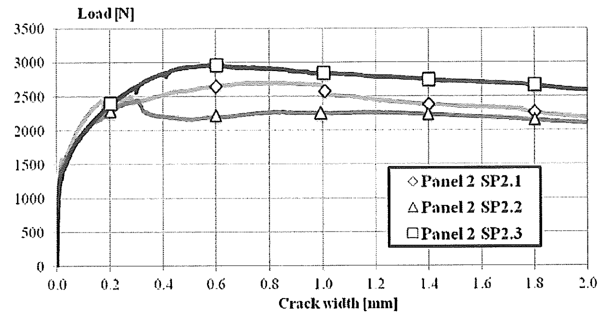

Figure 5: Test results specimens from Panel 2 (up to 2 mm)

Panel 3 [45° guides]

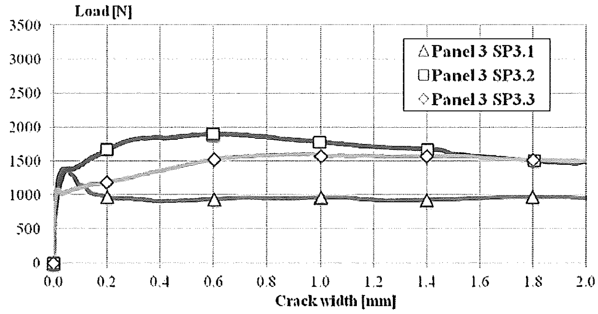

Figure 6: Test results specimens from Panel 3 (up to 2 mm)

The curves presented above illustrate that the pre-cracking behaviour is almost the same for all the specimens, since the contribution of fibres occurs after the loss of stiffness due to the cracking of the matrix. In the post-cracking stage, the fibres are activated and an hardening behaviour is exhibited, except for specimen SP3.1. Specimens extracted from Panel 1 (straight guides) and Panel 2 (free flow) show a similar behaviour, as is shown in Figure 7. Concerning the specimens extracted from Panel 3: their performance was the weakest, as expected, since the guides were oriented in an angle of 45 degrees.

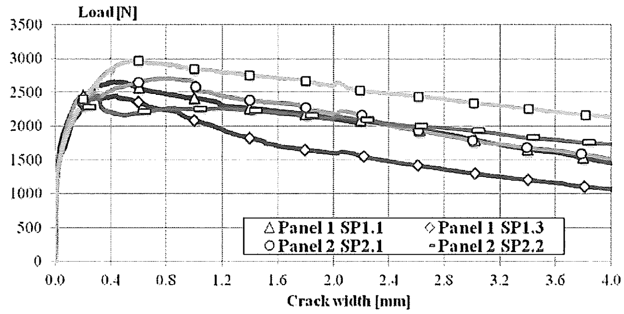

Figure 7: Test-results specimens from Panel 1 and Panel 2 (up to 4 mm)

4. ORIENTATION AND DISTRIBUTION OF THE FIBRES

4.1 Image analysis

Information regarding fibres' distribution and orientation in the cross-sections is necessary to analyse the influence of the three different casting procedures. For this, the specimens were cut after testing, as close as possible to the cracked section (25 mm behind the notch). The cut surfaces were polished and analysed using an optical method. The method consists in taking pictures of the cut-section with a high resolution camera. Fibres exposed to the flash light reflect it, while the concrete matrix absorbs it. The result is a picture on which each fibre can be distinguished. With the image-analysis programme 'Fiji' (http://fiji.sc), fibre's geometrical characteristics can be extracted and, consequently, their orientation can be determined.

$$\eta_\theta = \frac{1}{N}\sum_{i=1}^{N} \cos\theta_i = \frac{1}{N}\sum_{i=1}^{N} \frac{d_f}{d_{f2}}$$

Where N is the total amount of fibres in the cross-section and θ_i is the orientation angle of each fibre i having d_f and d_{f2} as the smallest and largest axes of the projected ellipse, respectively; an example of an analysis shows Figure 8. The distribution of fibres of a cross-section is calculated dividing the cross-section in six layers, as is shown in Figure 9.

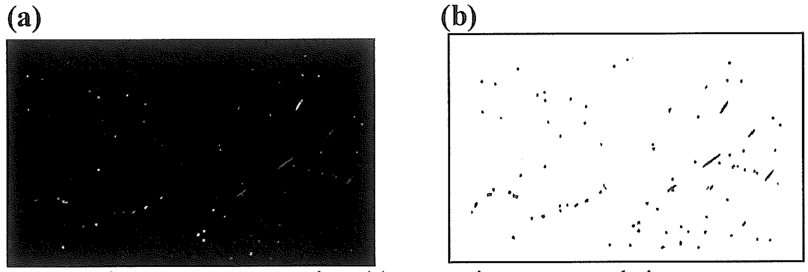

Fig. 8: Image processing: (a) converting to grayscale image; (b) adjusting threshold, removing noises, separating fibres stuck together

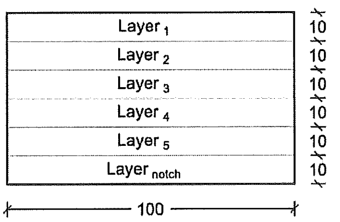

Fig. 9: Definition of the layers

4.2 Results of the image analysis

A higher number of fibres was counted in Specimen SP1.3 compared to SP1.1, but the fibres generally were less oriented. Therefore, the difference, in terms of flexural behaviour, between the two specimens was small. The guides' position affect the distribution and orientation of the fibres. As shown in Figure 1, one of the guides was placed inside specimen SP1.3, while in specimen SP1.1 no guides were present. Therefore, the fibres were more oriented in the first case due to the wall-effect exerted on both sides of the guides.

Table 4: Fibre distribution and orientation of different layers

	Position	SP 1.1	SP 1.3	SP 2.1	SP 2.2	SP 2.3	SP 3.1	SP 3.2	SP 3.3
	[mm]	n_{fibers}			n_{fibers}			n_{fibers}	
Total		73	77	74	81	97	92	61	99
L_1	0-10	10	10	8	8	12	6	8	13
L_3	20-30	6	9	9	10	15	17	5	10
L_3	20-30	17	18	11	16	11	15	6	22
L_4	30-40	17	20	15	16	21	17	19	19
L_5	40-50	15	13	15	20	19	28	12	20
L_{notch}	50-60	8	7	16	11	12	9	11	15
Orientation number		0.84	0.69	0.81	0.78	0.79	0.71	0.74	0.75

The orientation numbers of the specimens extracted from Panel 2 were similar, according to the conducted image analysis. The number of fibres decreased at an increasing distance from the casting point, i.e. SP2.1 is the specimen farthest from the casting point. In the casting zone, a higher shear rate has a shear thinning effect. In addition, 60 mm stiff steel fibres tend to entangle more easy compared to shorter fibres. Eventually, the specimens extracted from Panel 3 are the ones with the lowest orientation numbers. This confirms the expected orientation profile and the wall-effect induced by the guides. In all cases and within reasonable limits, the fibres were well-distributed within the cross-section.

4. CONCLUSIONS

This paper discussed an experimental study on how fibre orientation can be enhanced and how the casting procedure affects the orientation and consequently the post-cracking behaviour of self-compacting fibre reinforced concrete. Based on the experimental results the following conclusions can be drawn:

- It is possible to induce a preferable orientation of the fibres inserting plastic guides into the mould, taking advantages of the pronounced wall-effect.
- The behaviour and the results of the image analysis of specimens extracted from Panel 2 were coherent with the assumption that in a radial flow, the fibres rapidly tend to align perpendicularly to the flow direction.
- The results are coherent with the expected orientation, highlighting how the casting process influences the orientation. As expected, the responses of specimens extracted from Panels 1&2 are similar, while the ones from Panel 3 showed the worst performance. The tested specimens show a hardening behaviour in bending in all cases with the exception of Specimen 3.1.

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